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Part I: LASE Validation Experiment

Michael Garstang, P.I.
Kevin Levey, PhD Graduate Student
University of Virginia

Part II: Carbon Monoxide Distributions and Atmospheric Transports over Southern Africa

Michael Garstang, P.I.
Robert J. Swap, Co-P.I.
University of Virginia

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PART I

LASE Validation Experiment

Michael Garstang, P.I.
Kevin Levey
University of Virginia
Charlottesville, VA

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1. *Introduction*

Funding under NASA NAG1-1774 began October 1995. Supplemental funds were awarded in 1997 to pursue research utilizing the "Measurements of Air Pollution from Space (MAPS)" instrument to study carbon monoxide distributions over southern Africa. A no cost extension was granted in 1998. The grant terminated March 1999.

Work in both areas of research is continuing. Work under the LASE Validation Experiment was dependent upon the availability of the highest vertical and time resolution data obtainable from the LASE instrument. Obtaining these high resolution data took time and delayed the analysis. The analysis of the LASE validation experiment was extended to include additional LASE measurements (i.e., TARFOX and LASE/RS-80). The TARFOX data was from the 1996 experiment and the Southern Great Plains experiment of 1997. The purpose of the data processing was to establish firstly with the initial LASE validation data (1995) how well the RS-80 radiosonde data correlated with the LASE data, then re-calculate the statistics on the modified RS-80 data. It has been found that the RS-80 data has discrepancies or inconsistencies at certain temperatures, either reading humidities too high or too low. This method was then applied to the newer LASE data.

Initial results using the unmodified RS-80 and LASE validation data did not produce the results expected, i.e., the same results as the Langley team. An error in code was found and the data was re-run – the results were close to Langley's results. Initial results using modified RS-80 data has shown correlations between the LASE and modified RS-80 data to be slightly better, however, their statistical significance appears insignificant at this point.

Interpretation of the LASE measurements has been based upon the use of the Goddard Cumulus Ensemble (GCE) model. Considerable effort has been devoted to understanding and using this model. Details of this work follow below.

The work begun under NAG1-1774 will be completed under funding from the University of Virginia and will be contained in the doctoral dissertation of Mr. Kevin Levey scheduled for completion in the fall of 1999. Any papers published in the reviewed literature based upon this doctoral research will follow.

Progress under the grant was reported in June 1998. This progress report is attached as part of the final report. Work under the grant during the past year has focused upon the use of the GCE model. This work is reported on below.

2. *LASE Data Usage in the Goddard Cumulus Ensemble Model*

This past year's efforts have focused on the usage of LASE validation data in the Goddard Cumulus Ensemble model. A brief background to the model will be discussed and the usefulness of LASE data as input data will be demonstrated.

Cess et al (1990) concluded in their work on the intercomparison of climate feedback processes that there is a need to improve the treatment of clouds in global circulation models (GCM's) for reliable climate simulations. Cloud feedback processes are complex and most uncertain, but water vapor feedback found in recent GCM sensitivity studies appear relatively straightforward; that is, all GCMs have essentially shown a positive water vapor feedback. However, there are many uncertainties in the GCM-simulated moisture fields because of crude parameterization of moist processes. GCMs, however, are not suitable for detailed climate feedback studies owing to *primitive moist parameterization*.

An alternative approach is to use cumulus ensemble models (CEMs). A CEM includes explicit cloud-scale dynamics, detailed microphysics, and sophisticated radiative transfer calculation based on physically determined cloud optical properties. CEMs also employ a large horizontal domain and fine (cloud resolving) spatial and temporal resolutions, so as to allow many cloud populations to develop simultaneously.

This is where the real value of LASE water vapor will be tested, that is, within CEMs, and much more specifically, in the initialization processes of these models where current initializations are based on very few real randomly spaced data sources such as radiosondes and gridded model data. The high resolution of the LASE water vapor measurements could provide useful information in the description of the mixed layer, especially where clouds are present. This information may prove to be critical for the initialization process of such models, which currently use the "warm bubble" or "cool pool" theory (Tao et al 1991) to initialize the formation and growth of clouds. Instead of using such theories, real data measured in the field may give some indication as to real atmospheric processes occurring during cloud formation and growth and can then be used to initialize the convection during the model runs.

Traditionally, cumulus ensemble models have been used to study the dynamics of cumulus convection and the interaction between cumulus convection and the large-scale motion (e.g., Yamasaki 1975; Soong and Ogura 1980). Tao et al (1991) undertook a numerical simulation of a subtropical squall line over the Taiwan Strait during TAMEX. They investigated microphysical processes, longwave radiative cooling, heat and moisture fluxes from the ocean and pre-storm mesoscale convergence lifting. The results form the CEM runs, and using the "cool pool" theory, showed that the order of importance of each process to the total surface precipitation, beginning with the most important, is microphysics, longwave radiative transfer, heat and moisture input from the ocean, and pre-storm mesoscale convergence lifting. Hence, it is the microphysical processes that are most important and therefore, LASE water vapor data may prove to be critical during the initialization processes of any CEM. This will be discussed in more detail in the following section.

2.1 The Goddard Cumulus Ensemble Model

The study of the dynamic and microphysical processes associated with mesoscale convective systems has evolved over the past two decades using convective scale models. Two

basic features of such models are that they are non-hydrostatic and that they include a good representation of microphysical processes. They are non-hydrostatic since the vertical and horizontal scales of convection are similar. The Goddard Cumulus Ensemble (GCE) is such a model.

The GCE model is based on a set of non-hydrostatic and anelastic equations for continuity, momentum, potential temperature, and water vapor. Five conservation equations are also included in the model for cloud water (small cloud droplets), cloud ice (small ice crystals), rain, snow (density 0.1 gcm^{-3}), and graupel (density 0.4 g cm^{-3}). The microphysics includes a parameterization of Kessler-type rainwater formation and ice-phase parameterization. The subgrid turbulence is parameterized based on works by Klemp and Wilhelmson (1978) and modified by Soong and Ogura (1980).

The GCE model has been used to study cloud-environment interactions, cloud interaction and mergers, air-sea interaction, cloud draft structure and trace gas transport (Tao et al. 1993; Halverson et al. 1996).

A stretched vertical coordinate (height increments from 220-1050m) with 31 grid points is used in order to maximize resolution in the lowest levels. The top of the model may vary between 20-25 km. For typical 2-D simulations, 612 grid points are used in the horizontal, the central 504 of which comprise the fine-grid area with a constant 750 m resolution. A Galilean transformation (the storm propagation speed is subtracted from the initial wind field) confines the simulated cloud activity to the fine-grid region. Outside of this region, the grid is horizontally stretched with a ratio of 1.0625:1 between adjacent grid points. This results in a domain 1025 km wide. A staggered-grid arrangement (Arakawa C grid) is used in the model. A leapfrog time integration and second-order space derivative scheme (Chen, 1980) is used in the horizontal direction. A time smoother is adopted to avoid the problem of time-splitting. This coefficient is set to 0.1 with a time interval of 7.5 s.

2.2 Energy equations used in the GCE

1) The conservation for dry static energy, *s*, and latent heat, *-Lq* are derived below :

For any fixed (Eulerian) volume of air, the total quantity dQ/dt is conserved such that $dQ/dt = 0$ and

$$\frac{dQ}{dt} = -\frac{dq'}{dt}$$

Two conservation equations are obtained for the time rates of cumulus heating and drying within the volume of air :

$$Q_1 = \frac{\partial \bar{s}}{\partial t} + V \bullet \nabla s + \bar{\omega}\frac{\partial \bar{s}}{\partial p} = -V' \bullet \nabla s' - \omega'\frac{\partial s'}{dp} + L(c-e) + Q_r \tag{1}$$

$$Q_2 = -L[\frac{\partial \bar{q}}{\partial t} + V \bullet \nabla q + \bar{\omega}\frac{\partial \bar{q}}{dp}] = L(V' \bullet \nabla q') + L(\omega'\frac{\partial q'}{dp}) + L(c-e) \tag{2}$$

$$\frac{\partial s'}{\partial t} = L(c-e) + Q_r \tag{3}$$

$$\frac{\partial q'}{\partial t} = -L(c-e) \tag{4}$$

Equations (3) and (4) represent specific source/sink accounting for the net latent heating owing to condensation and evaporation L(c-e), and net radiative heating rate have replaced the local time rate of change terms on the right-hand side. It is common practice to neglect the heat sources/sinks from ice processes in (3) and (4) since the latent heat release from condensation is nearly an order of magnitude larger than that of fusion.

Q_1 represents the apparent sensible heat source and Q_2 the apparent moisture sink. Terms with an overbar denote large-scale averaged quantities which are measured from a network of radiosondes; terms with a prime are pertebation quantities which reflect unresolved cloud-scale processes. In a closed conservative volume, the collective effects of the pertebation processes must account for the heating and drying diagnosed from the larger-scale terms. Up to now these effects cannot be directly measured and are thus inferred from the ensemble-averaged terms. However, LASE data may shed light on the water vapor involved in these processes as far as the measured high resolution concentrations are distributed. Water vapor vertical profiles discussed earlier in this report, have shown great structure in both space and time. LASE data at high resolutions may help us initialize the model with real data and in a superior way as is presently the case. The following section will explain this in more detail.

2.3 Subgrid-scale Turbulence

The subgrid-scale turbulence employed in the GCE is based on work by Deardorff (1975), Klemp and Welhelmson (1978), and Soong and Ogura (1980). Their approach includes solving a prognostic equation for subgrid kinetic energy (E), which is then used to specify the eddy coefficients (K_m). The effect of condensation on the generation of subgrid-scale kinetic energy is also included in the model.

Where a grid point is saturated, the following vertical turbulence diffusion equations are used: Eq. 5 is on top and Eq. 6 is the second equation.

$$-\frac{\partial}{\partial z}\overline{w''\theta''} \approx \frac{\partial}{\partial z}K_h\frac{\partial\theta_e}{\partial z} \times \left(1+\frac{\varepsilon L^2 q_v}{c_p R_d T^2}\right)^{-1}$$

$$-\frac{\partial}{\partial z}\overline{w''q_v''} \approx \frac{\partial}{\partial z}K_h\frac{\partial\theta_e}{\partial z} \times \left(1+\frac{\varepsilon L^2 q_v}{c_p R_d T^2}\right)^{-1} \times \frac{\varepsilon L q_v}{R_d T\theta}$$

The derivation of these equations can be found in Klemp and Wilhelmson (1978).

2.4 Heat and Moisture Fluxes from the Ocean Surface

The diffusion terms D_{qv} and Dq used in the sub-grid scale equations (not shown) include surface heat and moisture at the lower boundary of the model obtained from bulk formulations. The vertical flux of sensible heat from the sea surface is assumed to take the form:

$$(\overline{w''\theta''})_o = -C_D V_o(T_s - T_o)/\bar{\pi} \tag{7}$$

Where C_D is the drag coefficient, Vo the surface windspeed, Ts the sea surface temperature, and To the air temperature at the anemometer level.

The moisture flux from the sea surface has a similar form:

$$(\overline{w''q_v''})_o = -C_D V_o(q_s - q_o) \tag{8}$$

Where q_o is the mixing ratio at the anemometer level and qs is the saturation mixing ratio at the sea surface temperature. In the model computations, the values of V_o, T_o and q_o are taken from the lowest grid level.

a) GCE initialization problems

LASE data may provide some valuable input to understanding the physical properties of the mixed layer and help to better initialize the GCEM. Most balloon ascent rates are about 300m min^{-1} requiring approximately an hour or more to reach tropopause heights in the tropics (~15km) (Garstang and Fitzjarrald, 1998). During this time, a significant fraction of the convective rain may fall. Balloons also do not ascent vertical and usually undergo horizontal displacements of 25 to 30km during any given sounding and hence, different environments of the sampling volume may be traversed during a given sounding. During a hone-hour sampling, convective systems may also undergo horizontal displacements within the sampling volume.

In almost all studies conducted thus far (Halverson et al., 1996) budget estimates of energy and water of convective clouds have been based on self-contained sounding networks. Hence, a degree of subjectivity is imposed upon the analysis by these various affects that cannot be adequately accounted for.

The coarse time and space scales of sounding observations prevents the direct computation of the cloud internal sources, sinks and fluxes of heat and moisture, (i.e., the unresolvable terms on the right-hand side of Eqs. (1) and (2). However, LASE data may prove invaluable in providing some solutions of the right-hands of these equations and verifying of the left-hand side part of these equations.

The high vertical and horizontal resolution of LASE water vapor data may also play a critical role in the initialization process of the GCEM. For a 2-D model run, the LASE data are not random, but sequential, and nowhere do water vapor (q_v) values have to be guessed or interpreted, unless LASE data are missing. They have been directly measured within the mixing layer or sub-cloud layer. Data for a vertical column are also instantaneous for each profile, there is no one-hour time lag and owing to the speed at which the data was collected, large volumes of data have been measured within minutes of each other. This makes LASE water vapor data valuable as input data to Eqs. (2), (6) and (8) which describe the three main scales at which different processes are taking place, but most importantly, describe better than ever before, some of the microphysical processes taking place in the sub-cloud or mixed layer.

Preliminary discussions with Tao (1998) have shown that there is the expectation of improving the initialization of the GCE model using high resolution LASE water vapor data derived from the LASE Validation project. It is hoped that the high resolution LASE data will solve some of the current initialization problems of the GCE model. Better initializations should improve the model's overall output performance, and this will hopefully be shown later this summer, when the model is run using the high resolution LASE data.

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3. Observations of CO at Midtropospheric Levels Over the South Atlantic and Adjacent Continents

Work based upon the September-October 1994 MAPS flight on the space shuttle Endeavor is described in the manuscript attached to this report. This manuscript, to be submitted for publication in a reviewed journal, constitutes the work completed under this section of the grant.